The Cluster Merger - Non-thermal Emission Connection

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Hypothesis: Cosmic-rays are accelerated (or re-accelerated) by merger shocks in galaxy clusters

1. Detection of Diffuse Non-thermal X-ray Component by 2 Methods

   (a) Cool clusters: hard residuals beyond the thermal continuum - IC 1262, Abell 1750

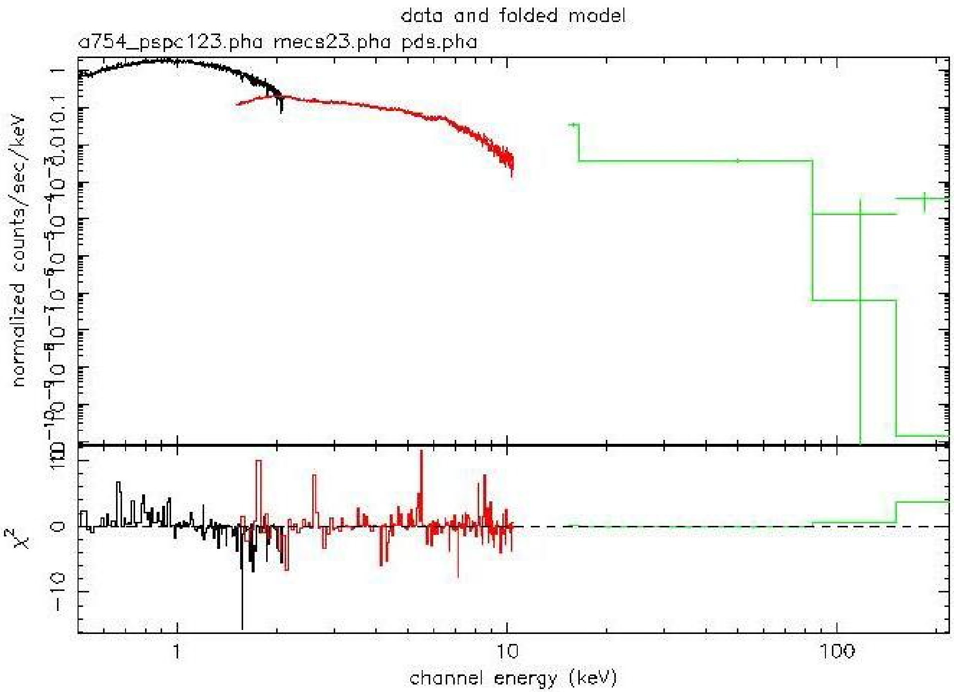
   (b) Hot clusters: soft residuals - Abell 754, Abell 2163

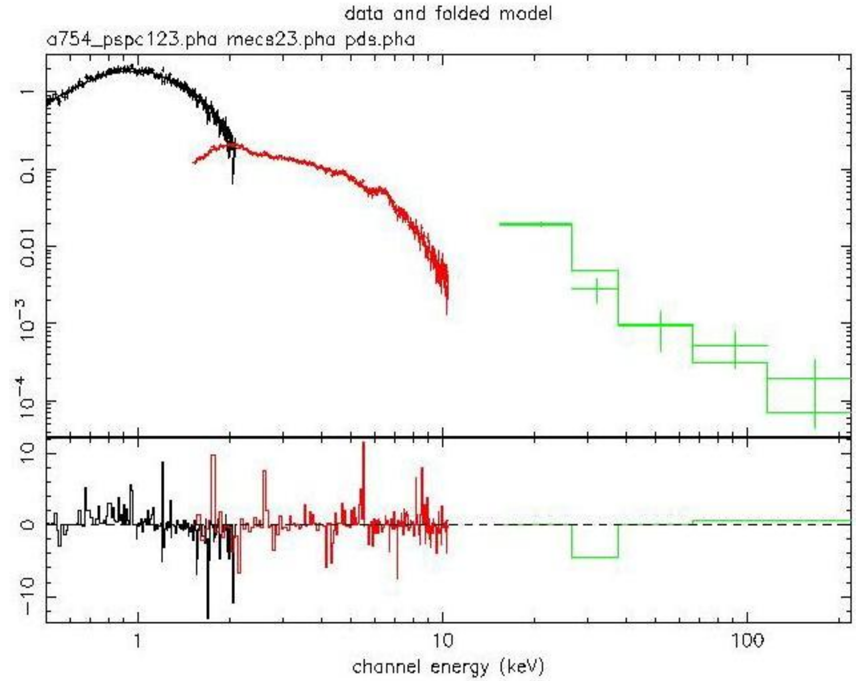
2. Non-thermal emission modeled with power law to obtain spectral index

3. Spectral index specifies Mach number for 1st order Fermi acceleration of cosmic-rays

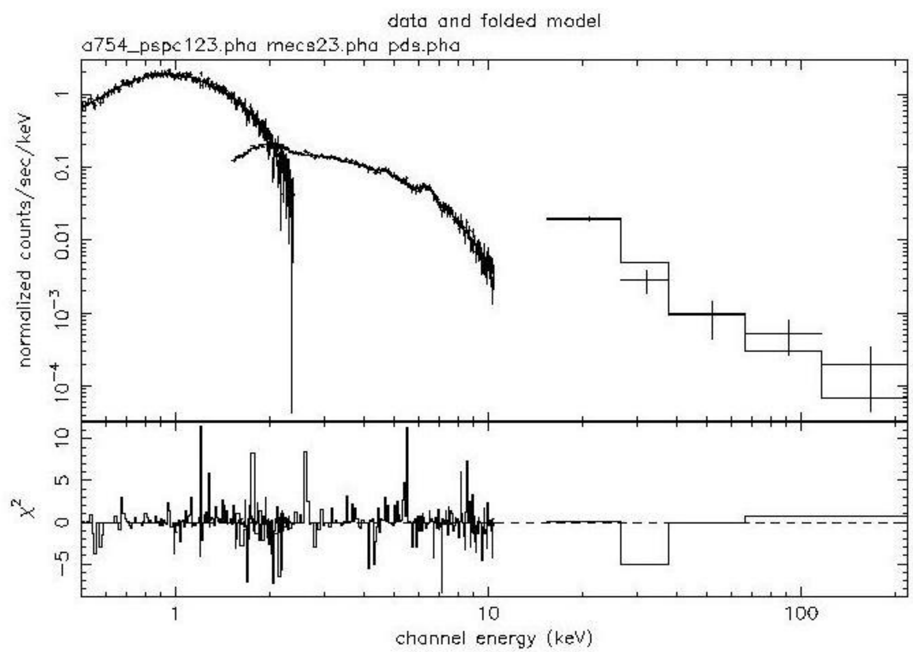
4. Temperature map provides calculation of Mach number for a merger model.

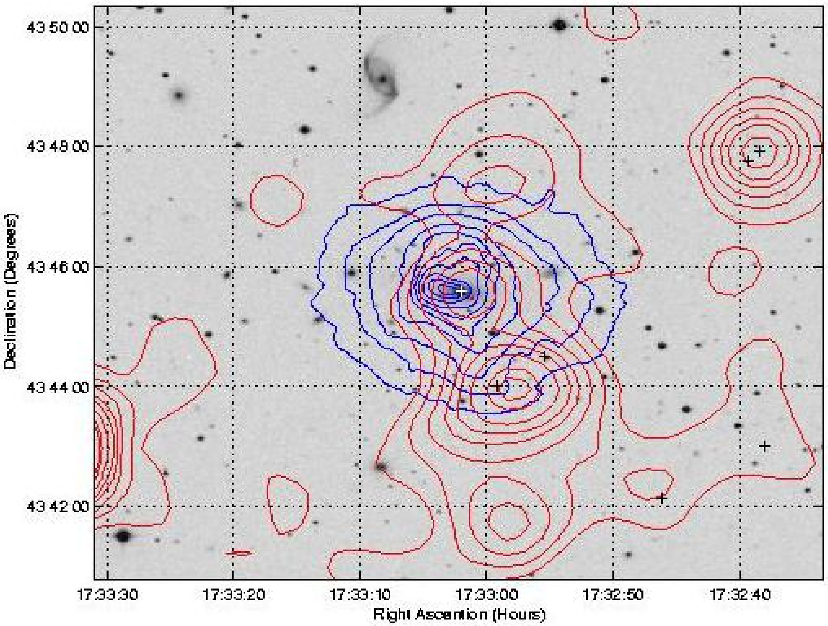
5. Thermal and non-thermal properties provide the merger history

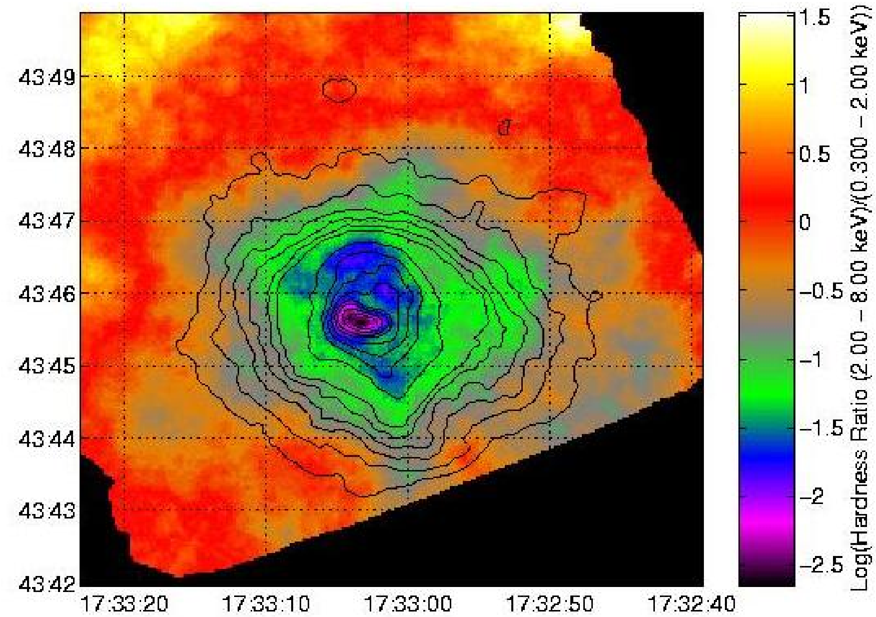




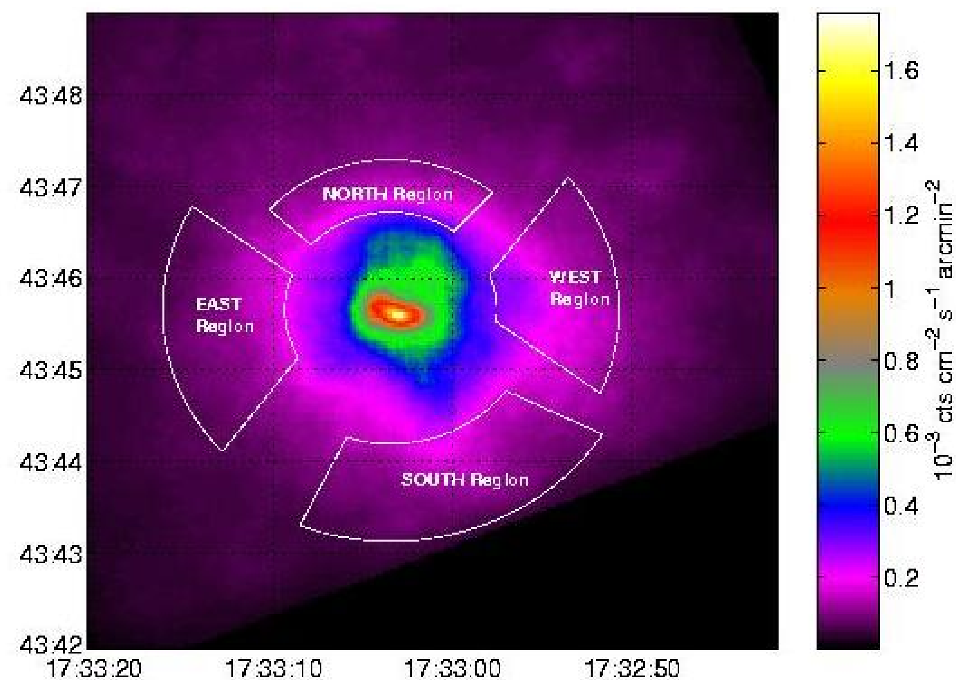
Broadband spectrum of Abell 754 from ROSAT and BeppoSAX. Clockwise: (1) single temperature thermal model-low and high energy residuals (2) addition of a powerlaw (from Einstein) for 26W20 models high energy residuals (3) addition of a second thermal component models low energy residuals better than a second Power law. <u>Note:</u> soft excess is centrally peaked - in between radio components. AGN contamination must be modeled!

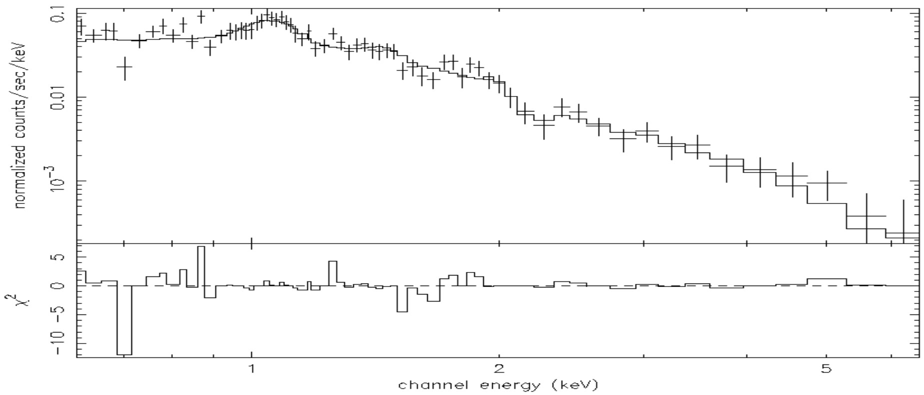




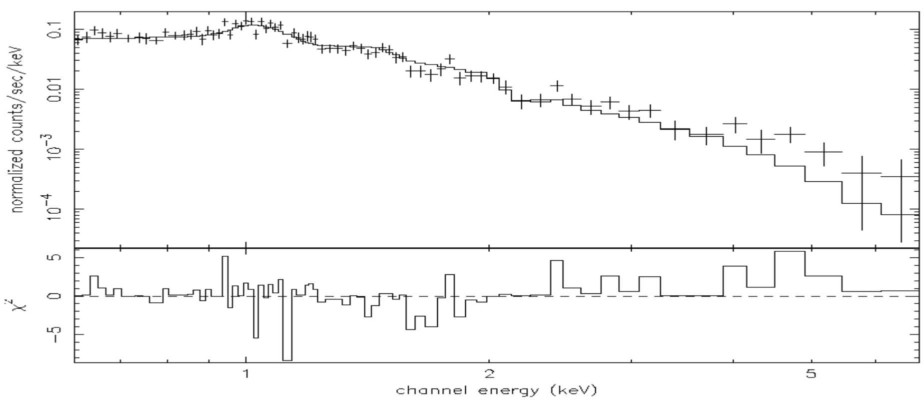


Imaging NT emission (with Chandra). Pick a cool (2 keV) cluster - IC1262 (z~.03)! <u>Above:</u> X-ray contours in blue, 330 MHZ contours in red (NVSS), and crosses are radio point sources. Radio halo extends > 400 kpc, $a_r = 1.8$. cD peculiar velocity is 453 km s^{-1} <u>Top Right:</u> Chandra hardness map. Note: compressed isophotes to the east - elongation to the south. <u>Bottom right:</u> Regions selected for further analysis.

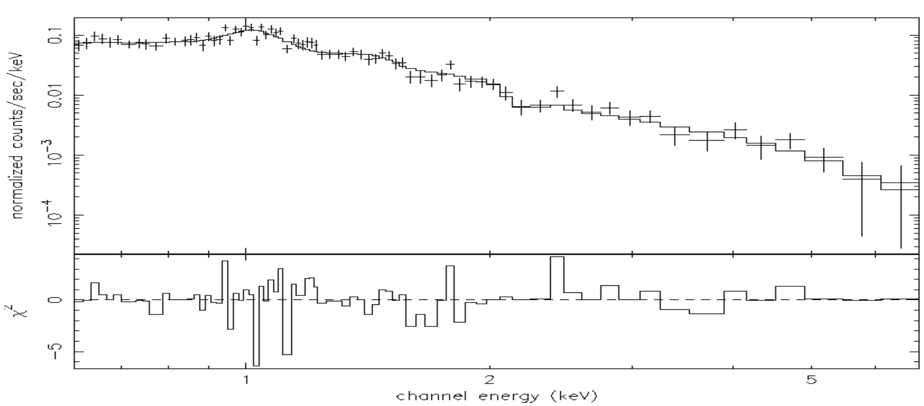




Single temperature model fit to Eastern region: 1.56 - 1.67 keV, 0.18 - 0.27 solar abd, X^2/dof = 114/101,



Southern extension. <u>Note:</u> high energy residuals: 1.57 - 1.67 keV, 0.23 - 0.32 solar abd, X^2/dof = 204/108. Note: MECS Shows NT component (>90% Confidence).



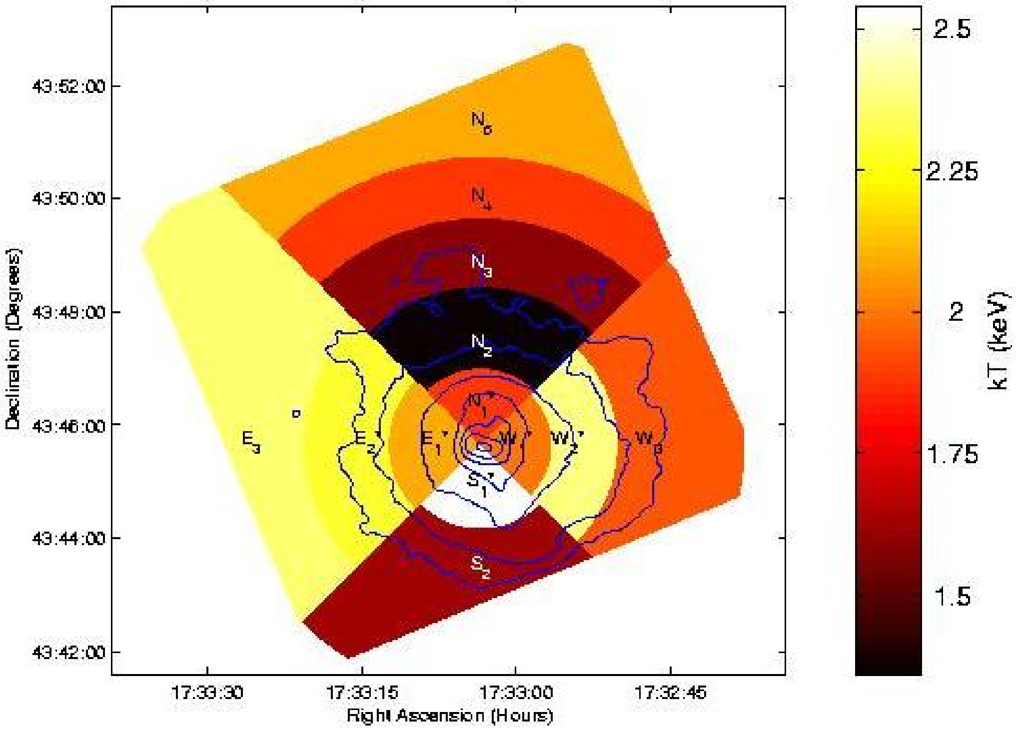
Fit to the Western region: 1.68 - 1.89 keV. 0.20 - 0.31 solar abd. X^2/dof = 126/108.

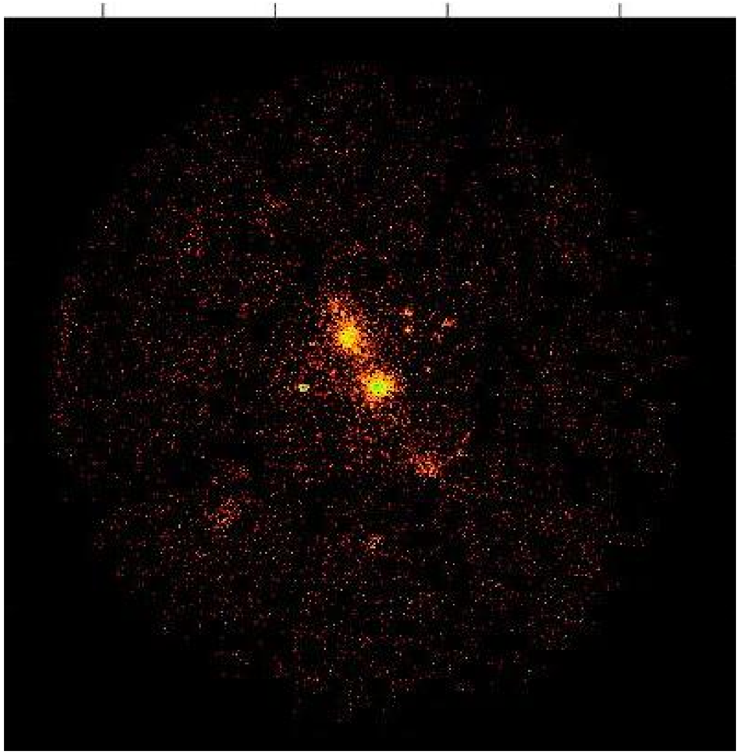
The Eastern and Western Regions show the southern residuals are not a calibration/background
Or effect.

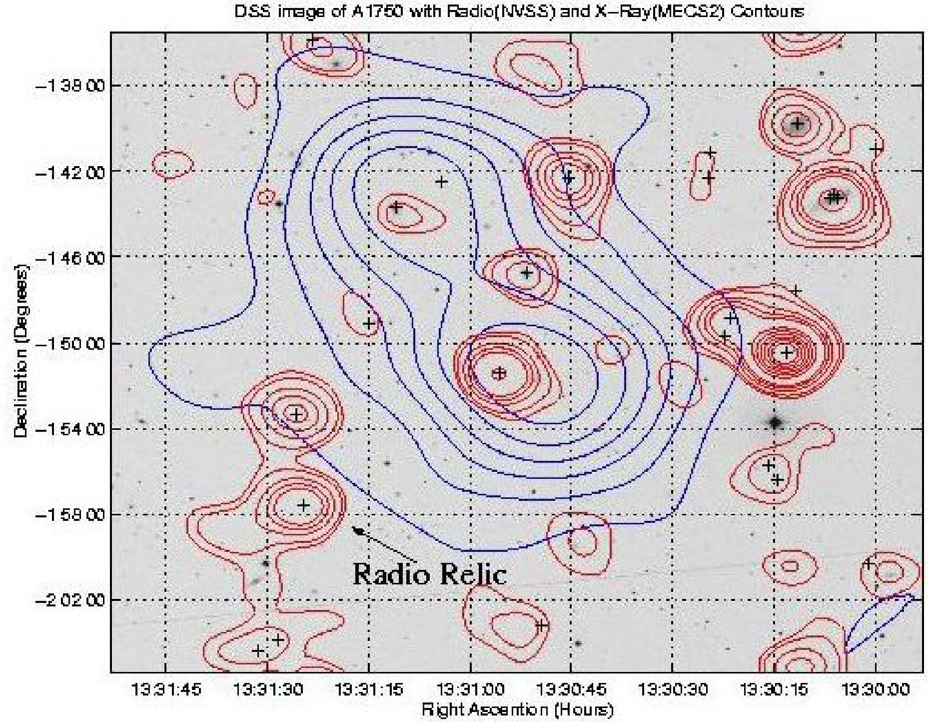
IC 1262 results (Hudson & Henriksen, 2003, ApJ, 595, 1)

•Hard residuals in Southern extension
•Best fit model has a non-thermal emission (NT), 7.0 - 10.6x10^{-5} ph cm^{-2} s^{-1} keV^{-1}
•Spectral index of NT powerlaw is 2.1 - 2.4
•NT emission is coincident with shocked gas
•Simulations indicate NT emission from primary Cosmic-ray electrons
•Morphology due to core oscillations from N-S merger (Tittley & Henriksen, 2004, (ApJ in press)

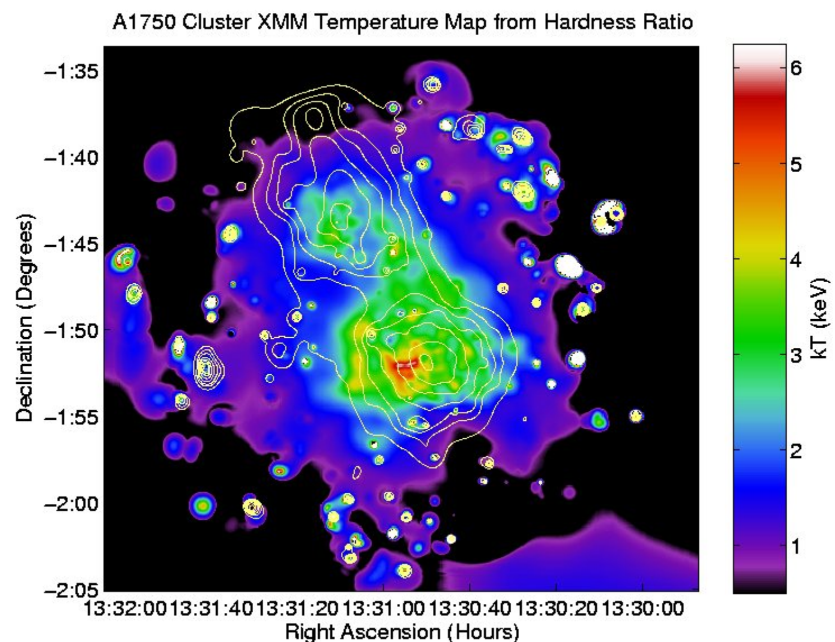
Chandra Temperature map. Shocked gas is visible in the Southern extension. Comparison to simulations implies merger 0.25 - 1 Gyr ago. Mass ratio of 1:2 - 1:4.

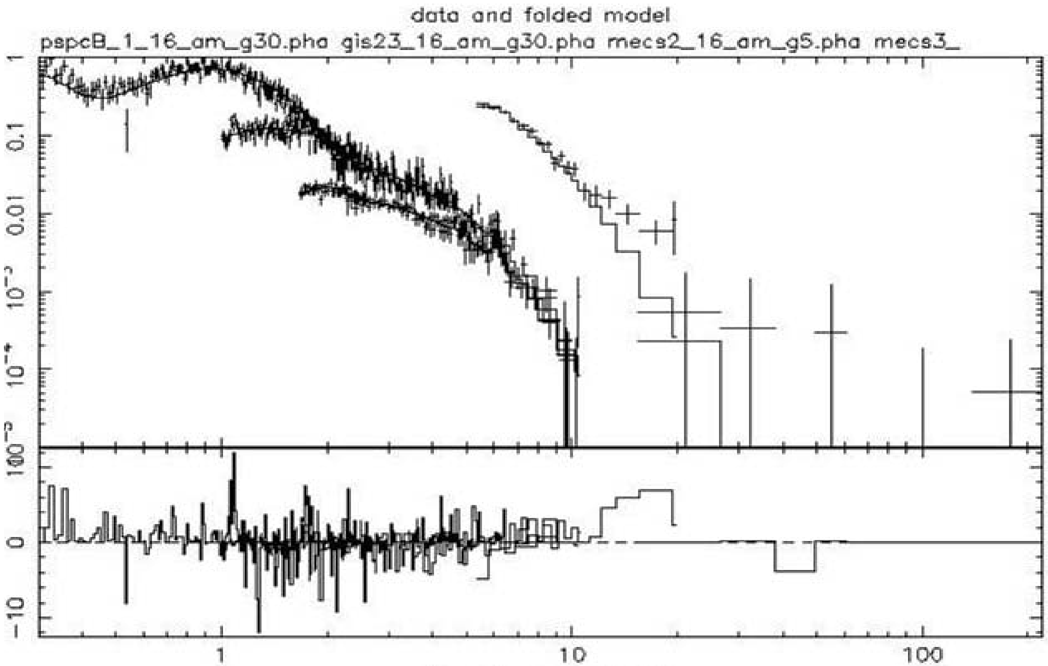


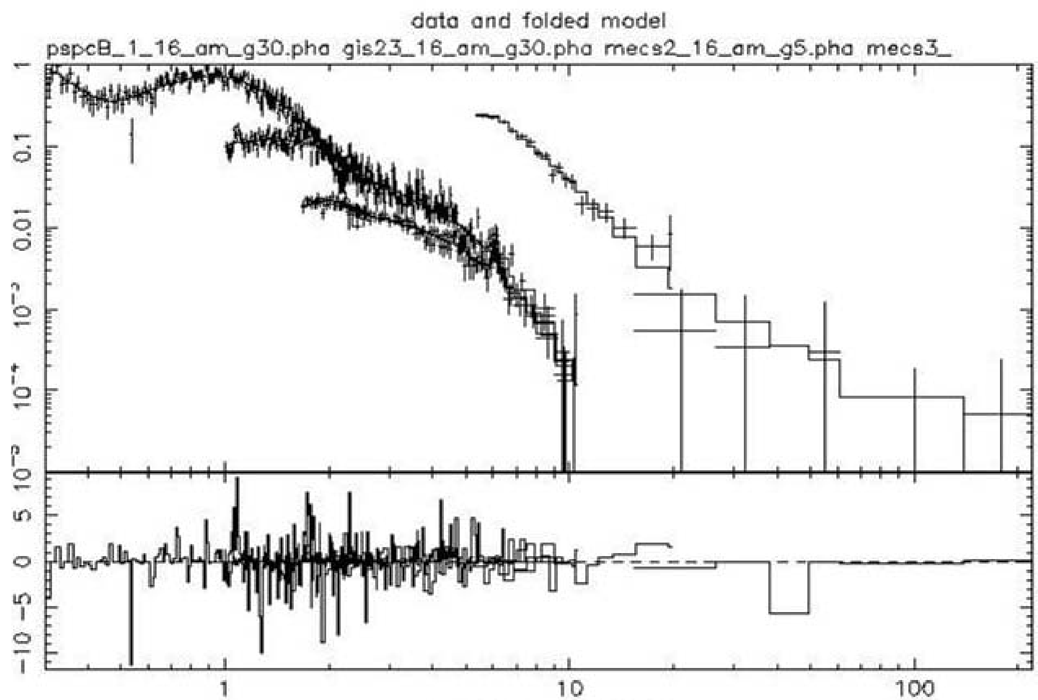




Abell 1750 (z = 0.0852) was a classic "bi-modal" morphology (pre-major merger) in PSPC. Above right: NVSS radio contours in red, BeppoSAX contours in blue. Radio relic to the east, 45.5 mJ, after subtracting point sources. Below right: Preliminary XMM temperature map shows hot regions around main cluster. No heating between main clusters as inferred from ASCA. Heating to the east. Suggests previous merger event.







<u>Top:</u> Single temperature model fit to (ROSAT) PSPC, (ASCA) GIS, (BeppoSax) MECS and PDS, and (RXTE) PCA spectrum.

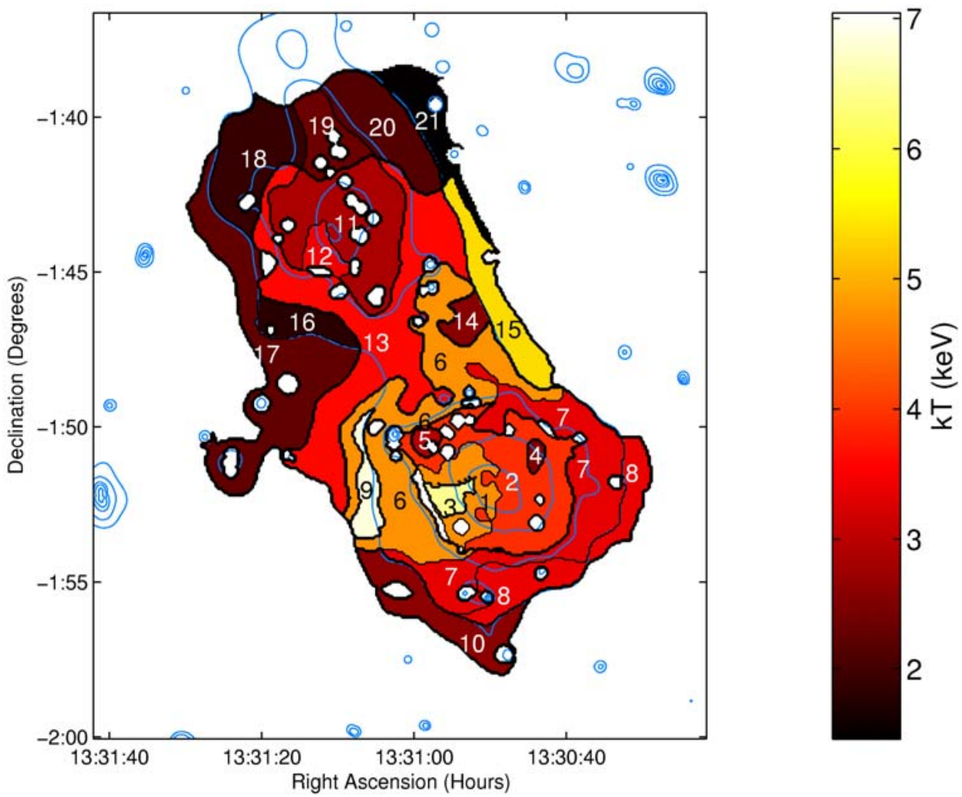
RXTE PCA spectrum of Abell 1750. **Shows Hard excess.**

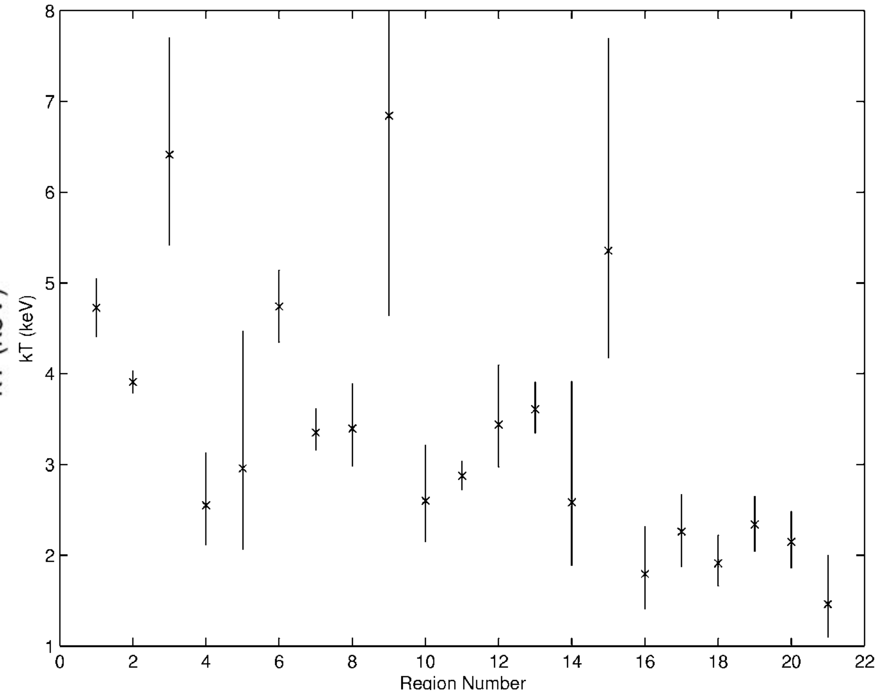
<u>Lower:</u> Power-law component added.

Spectral index is 1.9.

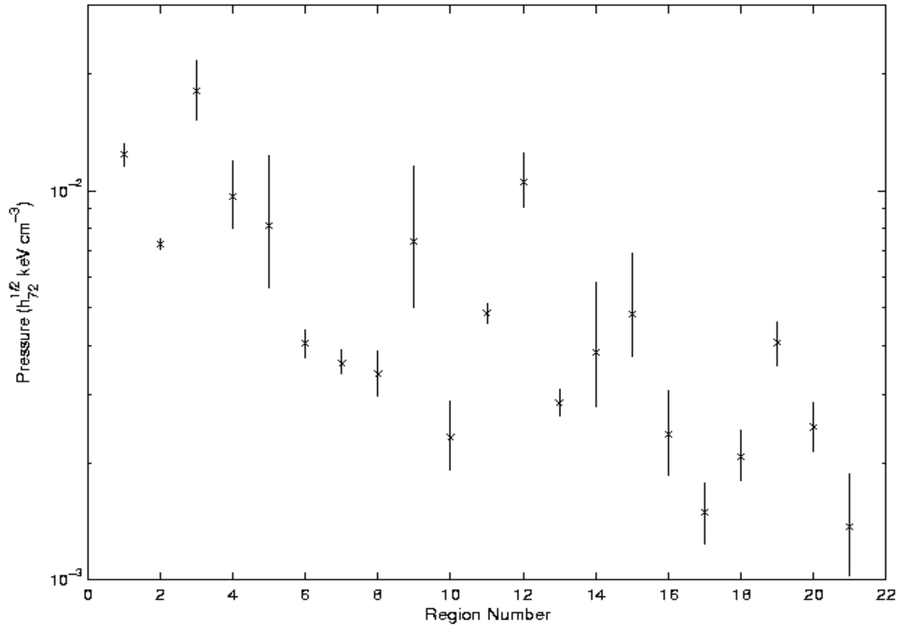
PCA CXB fluctuations were modeled.

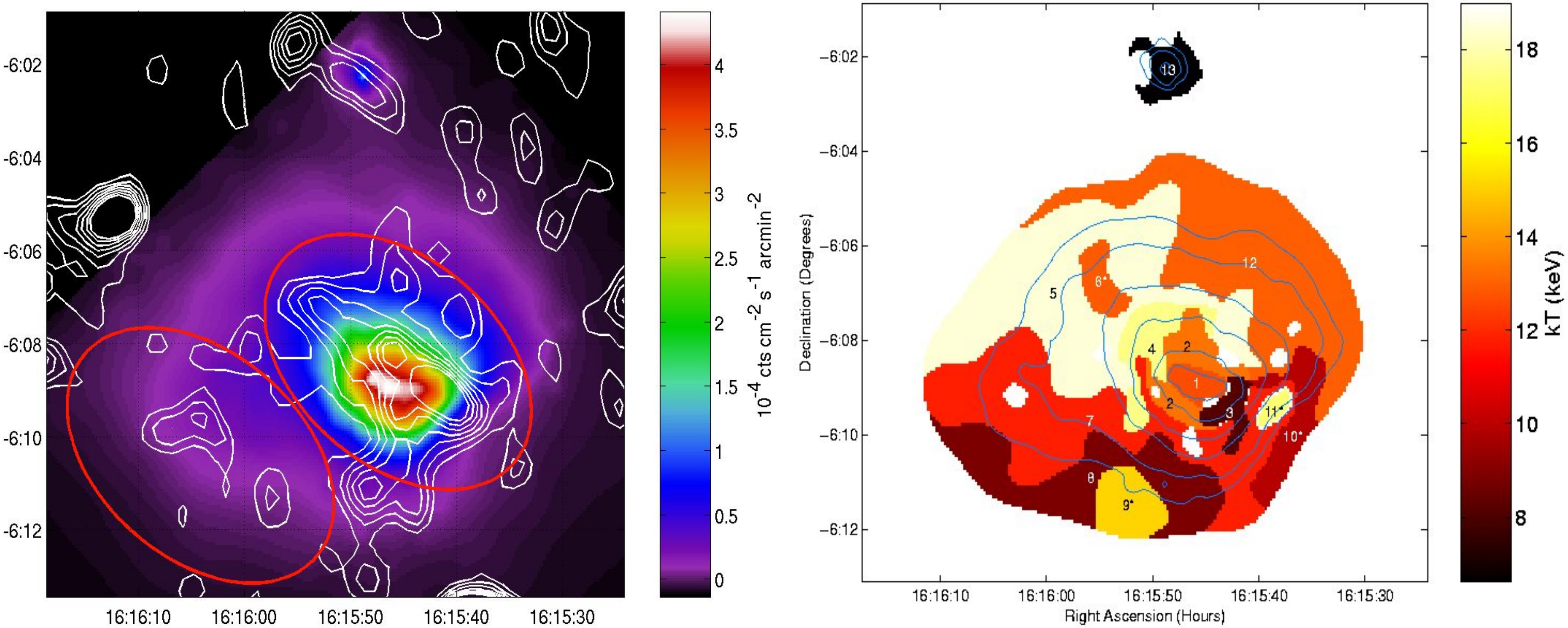
Point sources were modeled using XMM and PSPC for complete coverage of PCA fov. PS have flatter spectral index (~0.9) <u>Note:</u> PCA light curve is not variable.





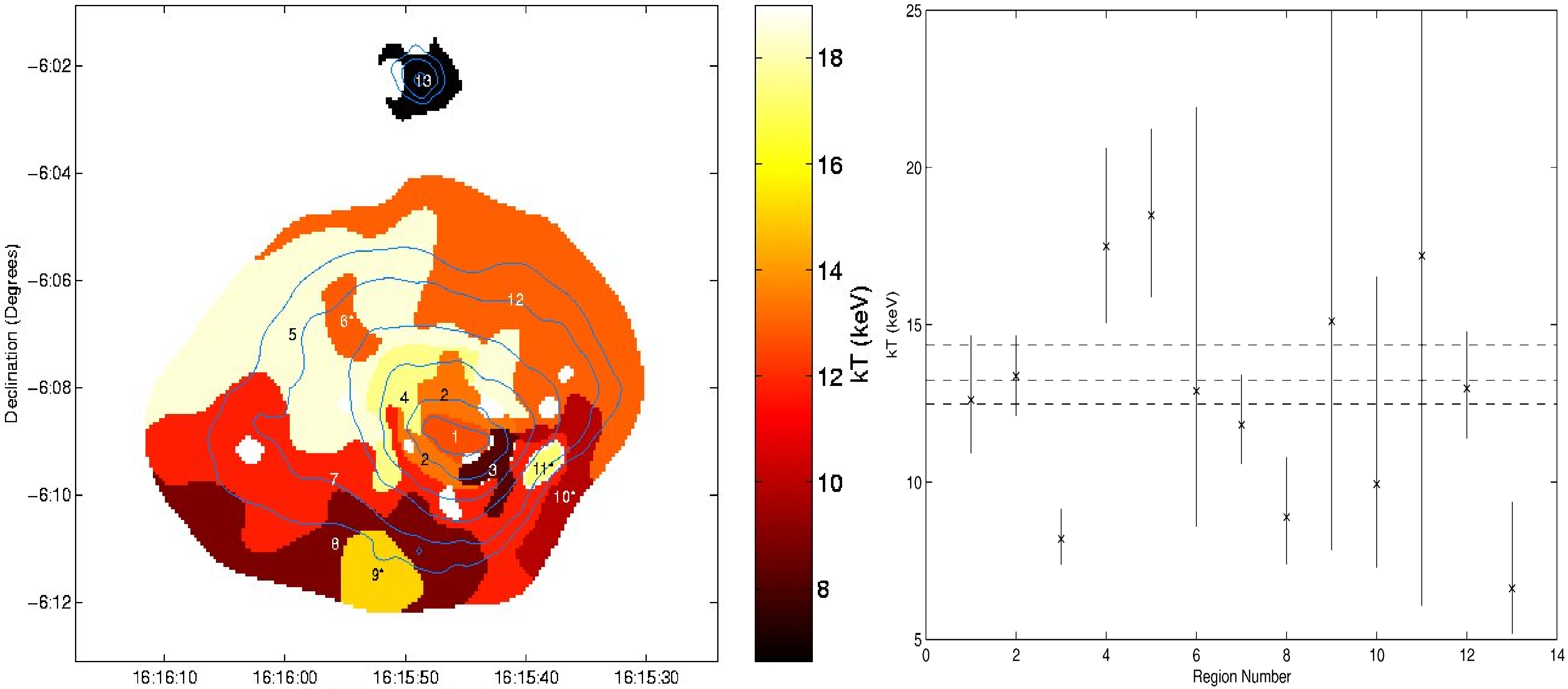
A1750 temperature map from XMM. Hottest regions are 3, 9, and 15. Regions 3/9 also represent high temperature, high pressure discontinuities (i.e., shocked gas). To the east of the peak of the main cluster. Multi-phase gas can not give the hard component in the PCA. The high T component, 6 keV, would have to be 80% of the total emission measure yet is only seen in localized regions 3,9, and possible 15.





<u>Above Left</u>: Abell 2163 color coded surface brightness map binned to maintain 3 sigma regions. Contours are NVSS radio. Red ellipses are the analyzed regions (on the radio halo and off the radio halo) Using Chandra spectra.

<u>Above Right</u>: Temperature map binned to maintain 5 sigma regions. Point sources Have been removed from both maps. On the radio halo, the addition of a steep power law (2.7 - 5.9) or second thermal component (0.2 keV) is a significant (99.8% confidence) improvement to the fit. Off the halo, only a single thermal component (12.2 keV) is needed.



Region 3 has much lower entropy compared to surrounding regions: 1,2,7, and 12. High temperature gas in regions 4,5 are the post-shock gas while region 3 is pre-shock. Thermal interpretation for soft component has problems if it originates in galaxies: (1) should see it in the off halo component, (2) too cool for giant ellipticals, (3) requires 10,000 dwarf ellipticals based on L_x-L_{opt} correlation. Temperature, 0.2 keV matches the XMM detections of filamentary gas. However, the average density of the 0.2 keV component is 5,200-127,200 relative to critical (for a flat Lambda CDM universe). A warm filament would be much less: 5 - 200. We conclude that the non-thermal interpretation is correct.

Rankine-Hugoniot Relations

1. $1/R_{obs} = [4(T_2/T_1 - 1)^2 + T_2/T_1]^{1/2} - 2(T_2/T_1 - 1)$

2. The compression ratio, R_{obs} is calculated from the temperature map.

3. $M_{obs} = [3R_{obs}/(4 - r)]^{1/2}$ gives the Mach number

4. Assuming 1st-order Fermi acceleration of the cosmic-rays

   $3/(2R_{obs} - 1) \approx \mu$ where μ is the energy spectral index.

6. μ can be compared to the spectral index measured from detections of synchrotron or Inverse-Compton emission.

Note: Thermal maps and Non-thermal maps are both indicators of merger history and may indicator separate episodes.

Abell 2163

μ is measured from the radio to be 2.36. This requires a Mach number of 2.27.

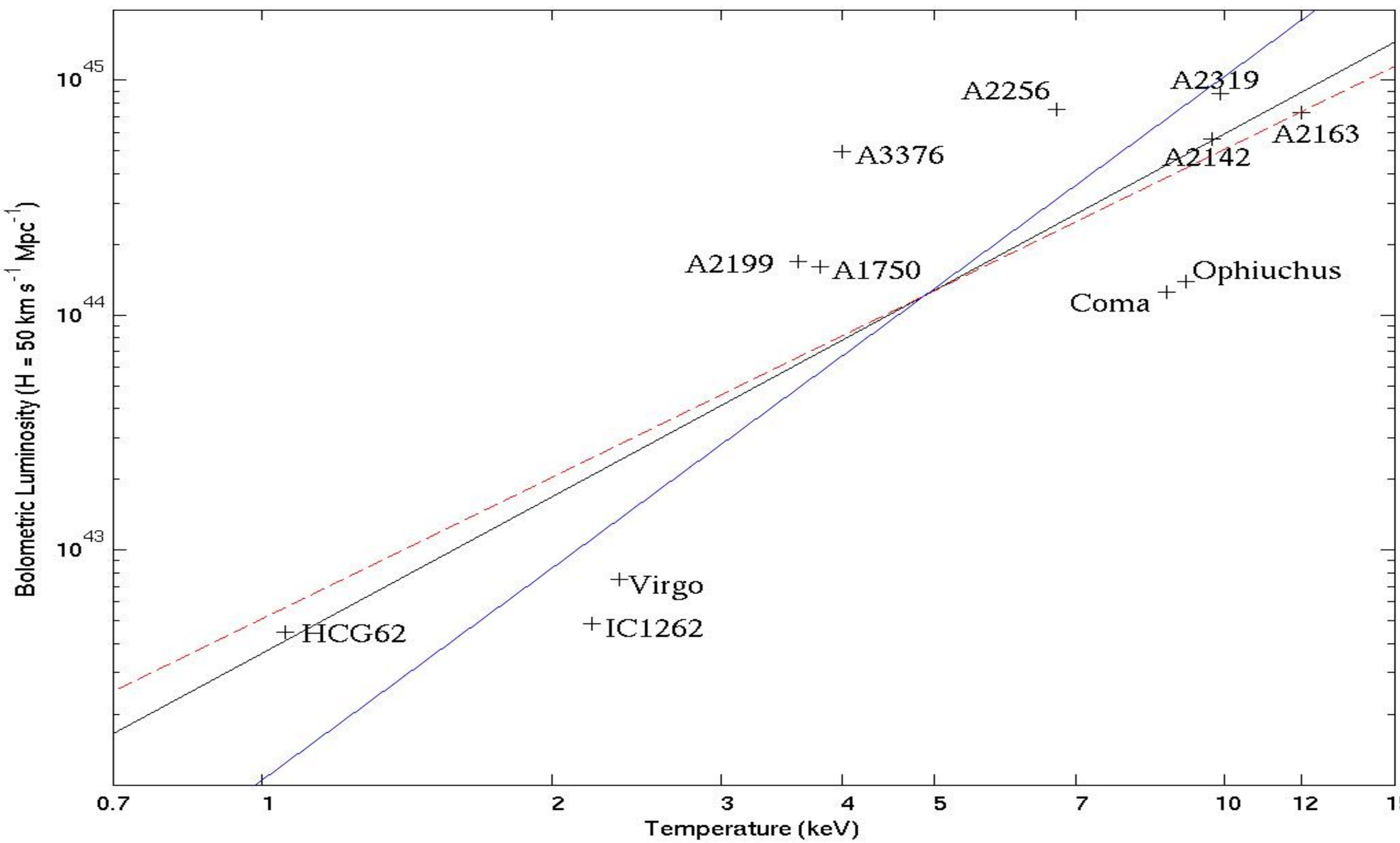
The best fit photon index for the inverse-Compton component is 2.7 - 5.9 (90% confidence). This requires a Mach number between 1.2 - 1.5.

Our merger model is that the coldest gas (region 3) is pre-shock and the hottest region (7) is post-shock. The calculated Mach number is 1.2 - 1.5 in agreement with the detected X-ray component.

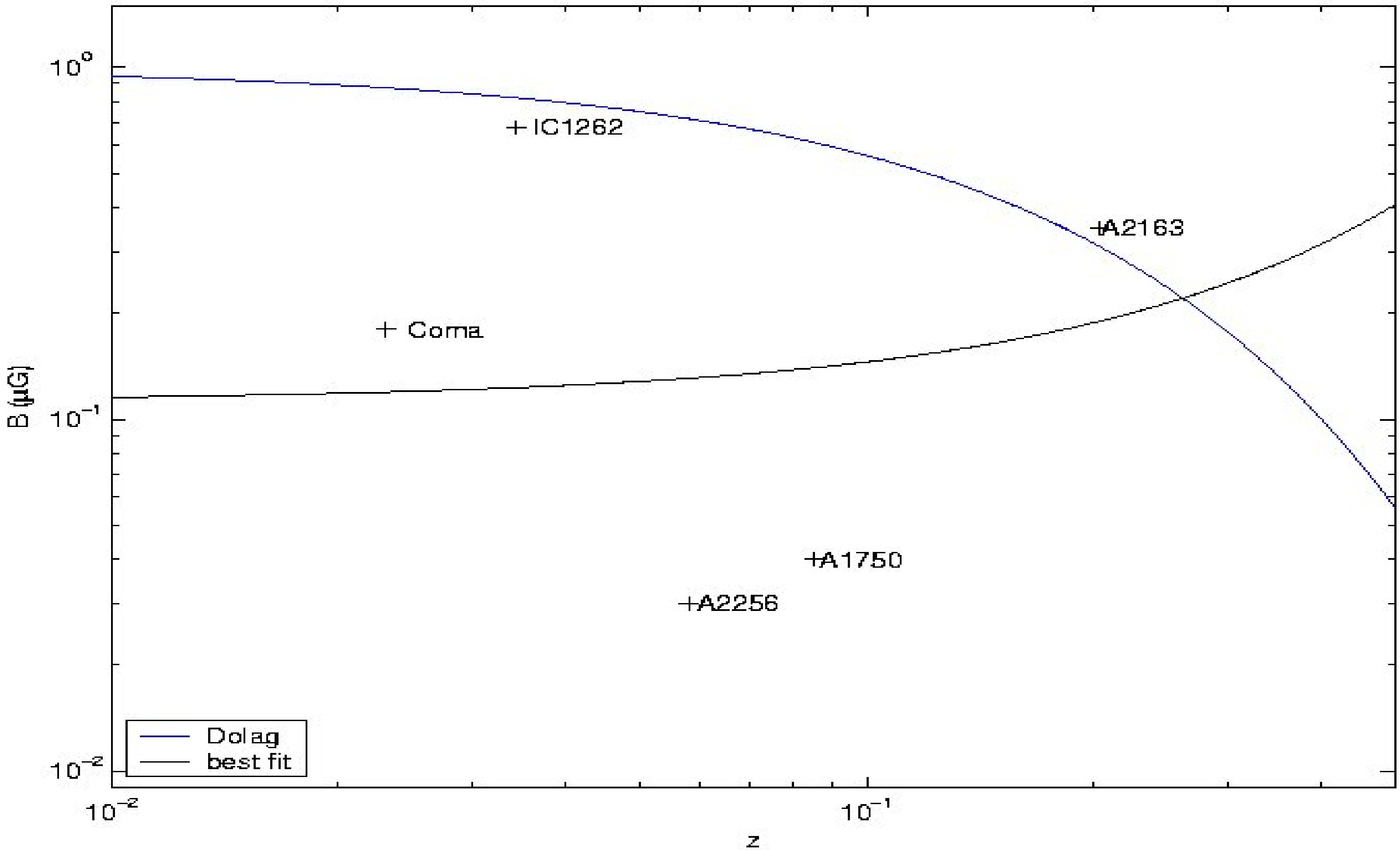
Conclude:

1) The shocked gas from the merger can account for the IC component but not the synchrotron component.

2) The synchrotron component is due to turbulence that follows the merger (Fujita et al.2004).



Black line is the best fit line with slope 2.2. The steeper line is predicted for non-thermal emission from secondary cosmic-ray electrons. The best fit favors primary cosmic-ray electrons though the correlation depends upon the only one group, HCG62 (Fukazawa et al. 2001) Coma, A2142, A2256, A3376, A2199, Virgo, and Ophiuchus are calculated from Nevalainen et al. (2004).



The assumption in these simulations is that the B field is frozen into The ICM and evolves along with the ICM. Radio and NT X-ray Measurements with similar resolution will allow calculating B(r) without assuming Equipartition (required to use only the radio). Comparison with $n_e(r)$ will check this And provide a comparison of $U_B(r)/U_{gas}(r)$ to evaulate the dynamical importance Of magnetic fields in the ICM.

Conclusions

1. Non-thermal X-ray emission detected in IC 1262, Abell 1750, and Abell 2163 associated with cluster merger

2. Soft excess detected in Abell 754 from embedded groups - new cluster component

3. Non-thermal X-ray emission co-spatial with radio halo in IC 1262 and Abell 2163

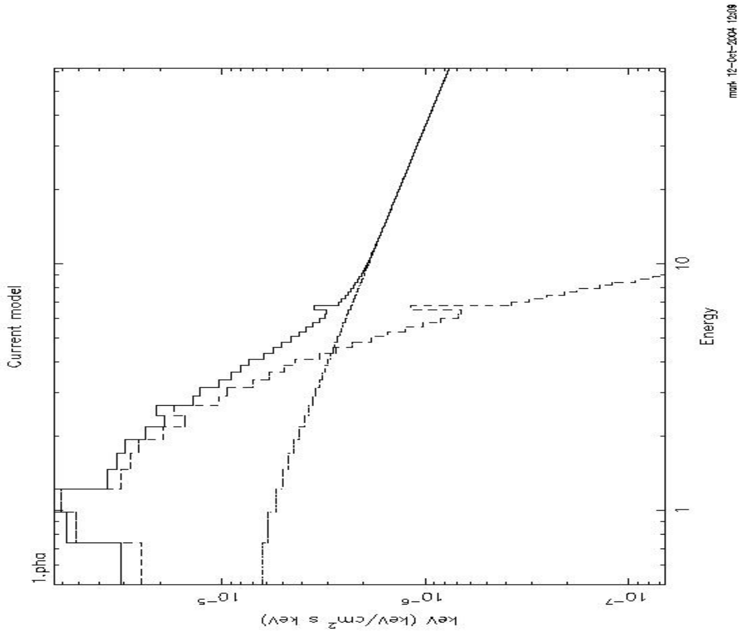
4. Non-thermal X-ray emission co-spatial with shocked gas in IC 1262: primary cosmic-rays from merger

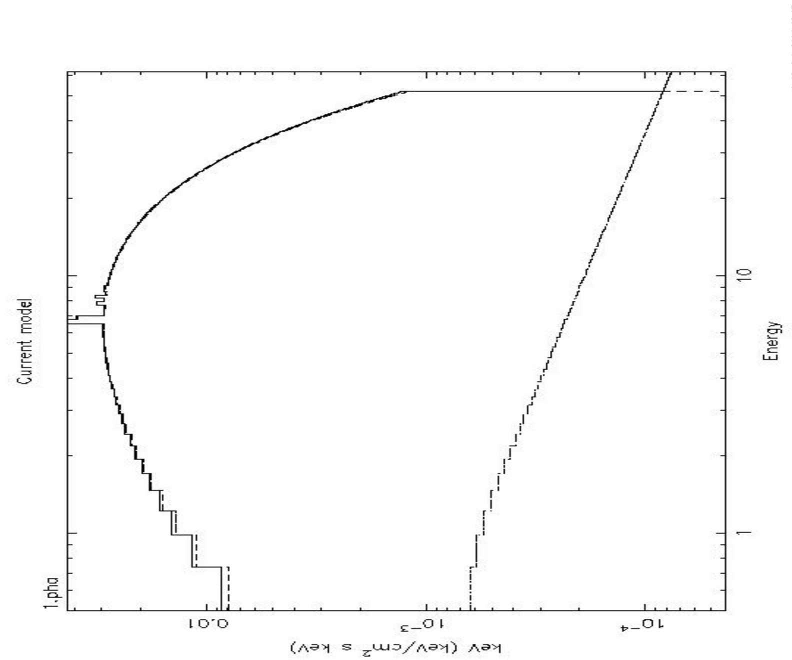
5. Spectral index for IC 1262 and Abell 1750 consistent with primary cosmic-ray electrons

6. First generation L_{nt} vs. T plot consistent with primary cosmic-rays. Under-sampled at low T

7. First generation B vs. Z plot does not *clearly* show evolution out to z ~ 1.

(Prospects for Constellation-X on Next Slide)





<u>Upper Left:</u> T = 1 keV, z = 20% Solar, bolometric flux = 10^{-13} ergs cm^{-2} s^{-1} +
power law with photon spectral index 2.5 and flux 2.5×10^{-14} ergs cm^{-2} s^{-1}

Con-X HXT has a thermal count rate of 8.6×10^{-4} and non-thermal count rate of 1.7×10^{-3}

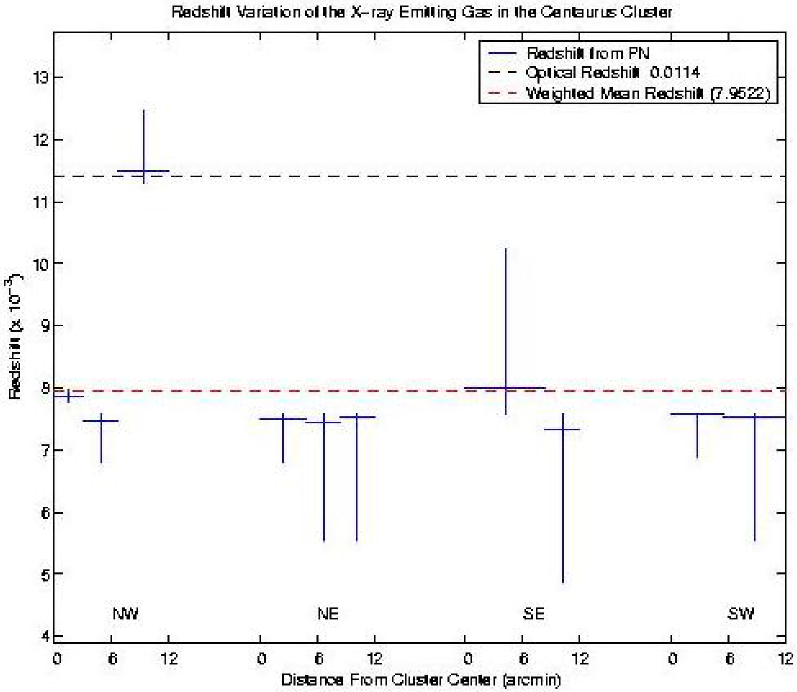
<u>Upper Right:</u> T = 10 keV, z = 20% Solar, bolometric flux = 1.4×10^{-10} ergs cm^{-2} s^{-1}
+ power law with photon spectral index 2.5 and flux 2.0×10^{-12} ergs cm^{-2} s^{-1}

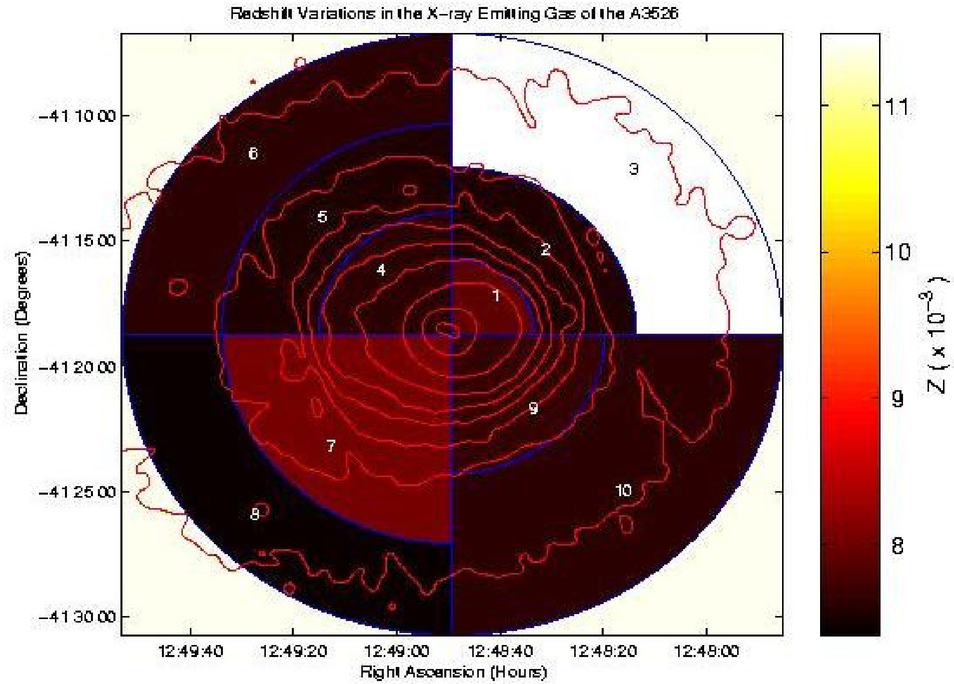
Thermal luminosity increases as $T^{3.15}$ while non-thermal luminosity increases as $T^{1.9}$ (primary Cosmic-ray electrons) and $T^{3.0}$ (secondary cosmic-ray electrons).

Con-X HXT has a thermal count rate of 29.1 counts/second and a non-thermal count rate
Of 0.14 counts/second.

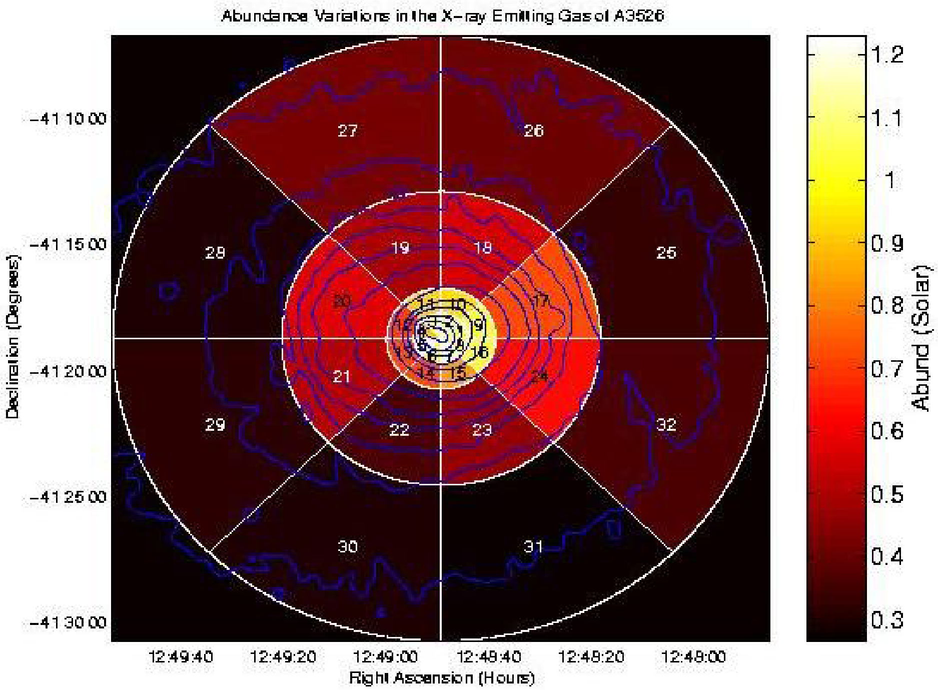
Conclude: HXT will be able to image NT emission only for cool clusters with <u>long</u> observations

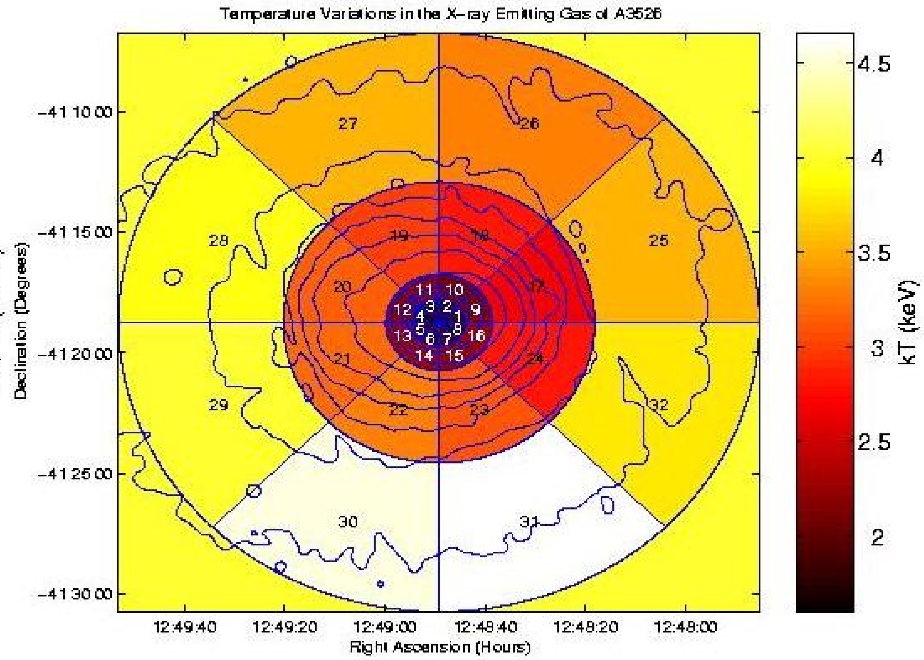
Direct Detection of Intracluster Gas Flow with XMM



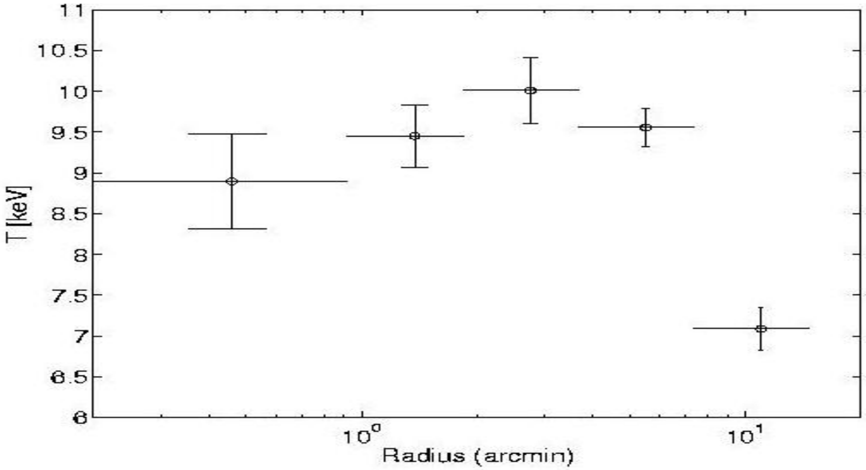


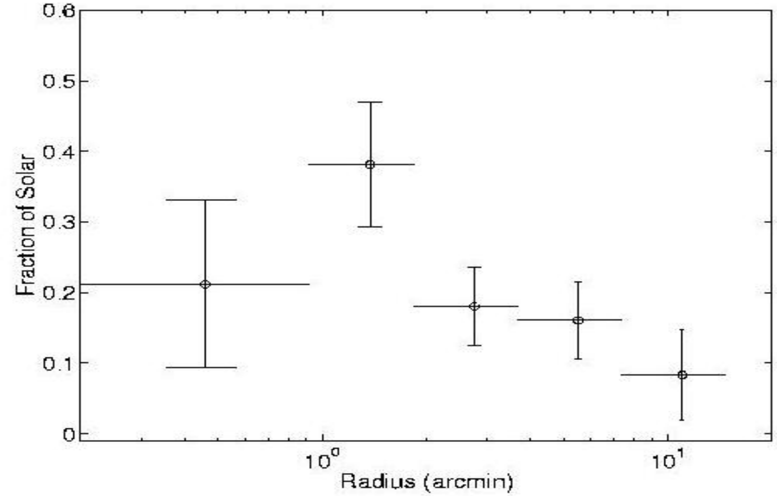
Region in the NW shows an outward flow of 1000 km s-1 in the direction of the “Great Attractor”. All other regions are consistent with a redshift of 0.008. Note Optical redshift!!!

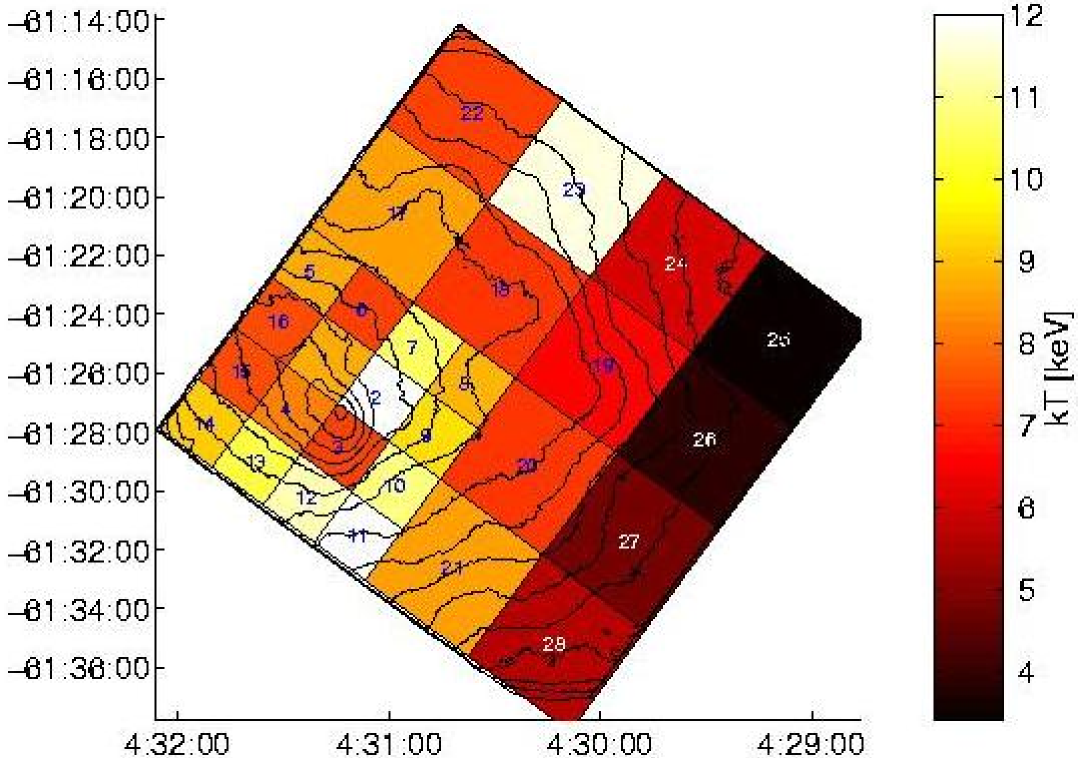


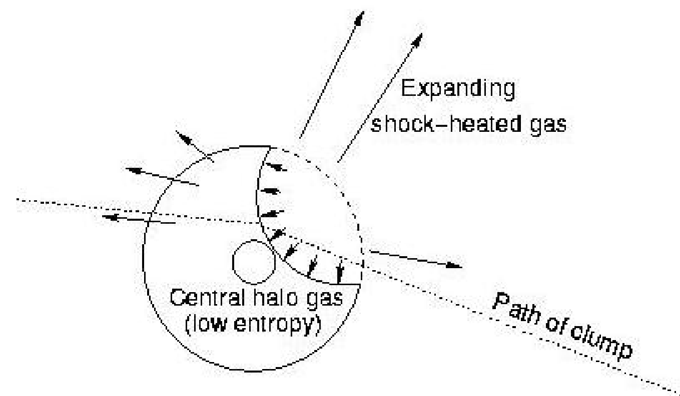


Signs of merger not present: (1) abundance gradient is centered, (2) Central temperature inversion is present. Simulations show that a Merger erases both through turbulent gas mixing. See Abell 3266

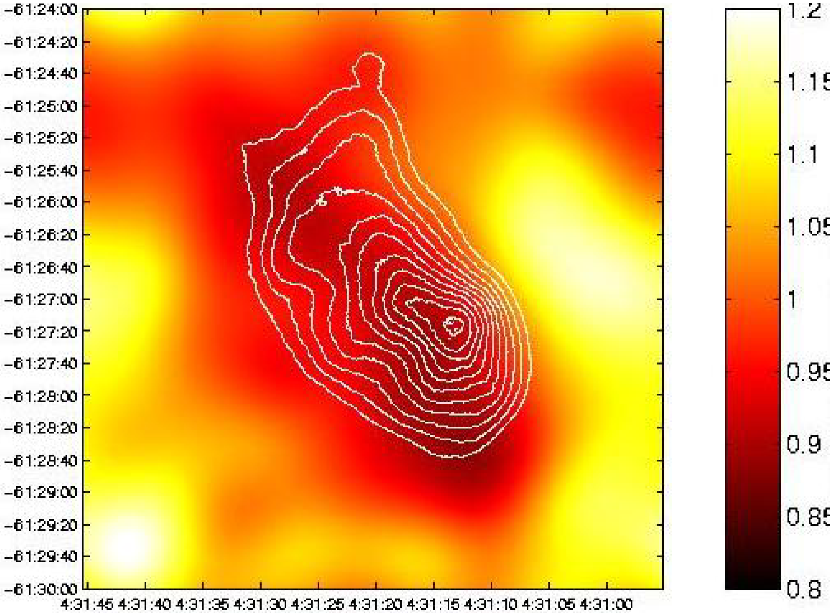


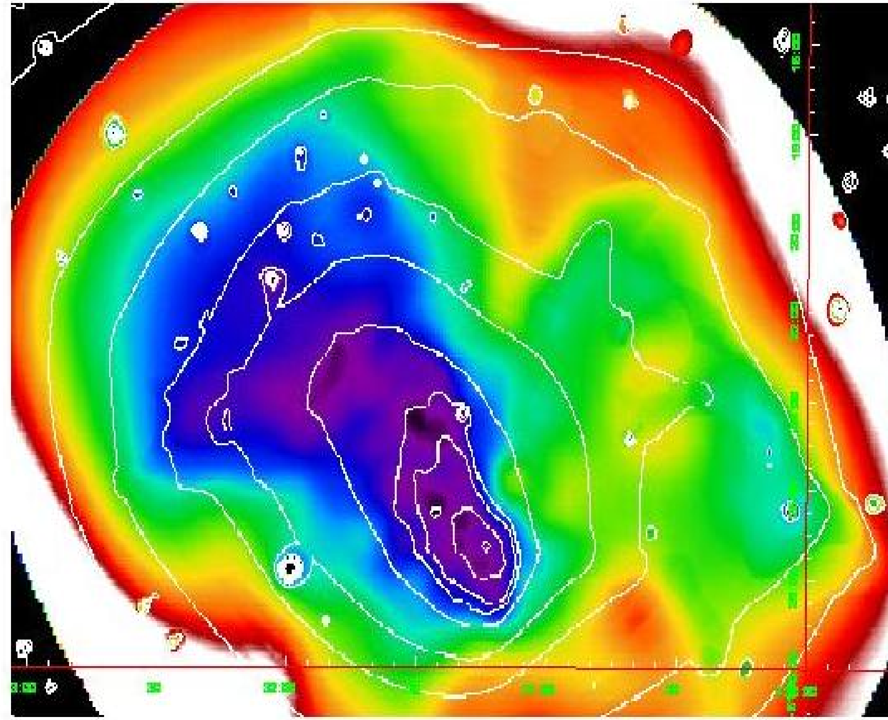




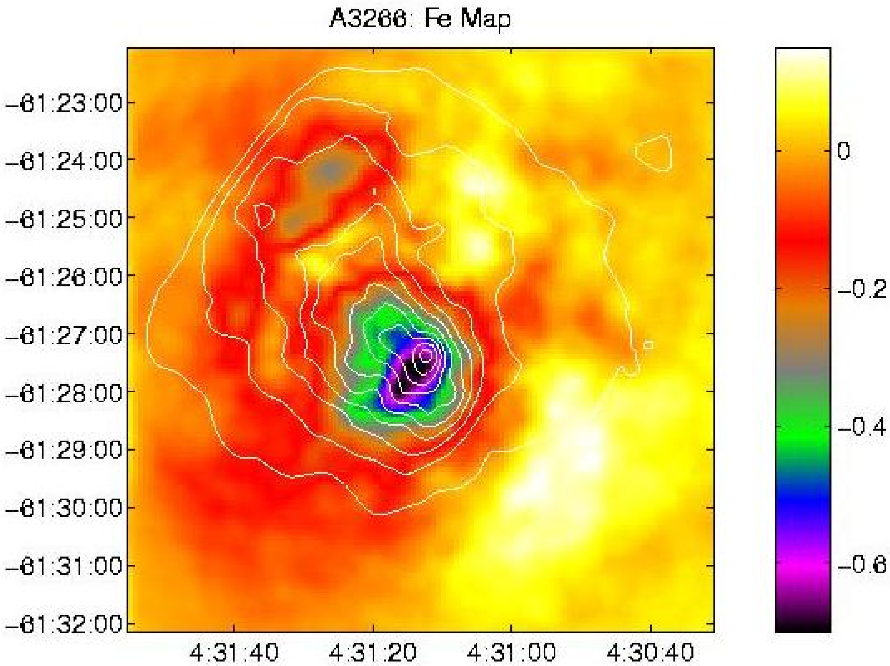


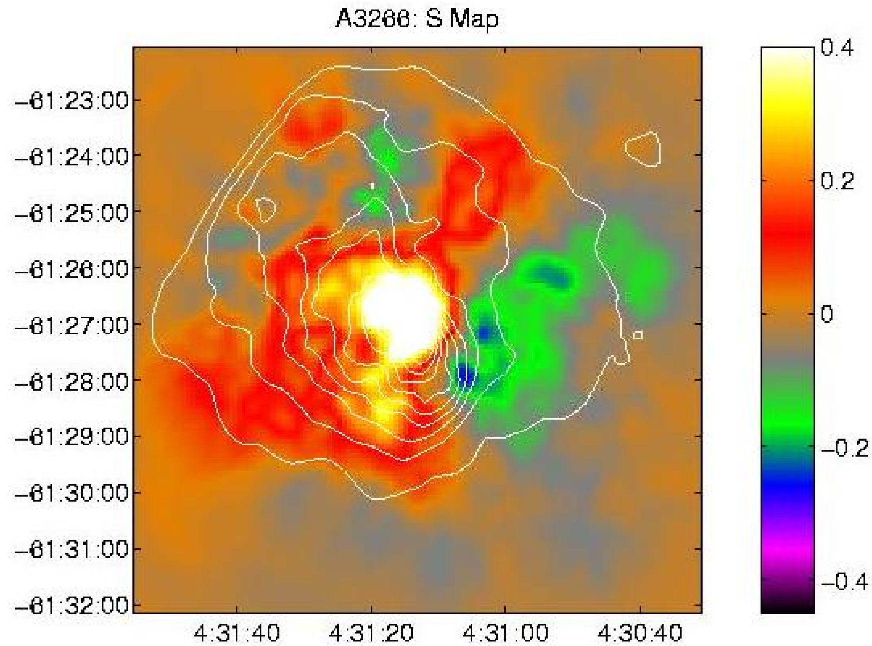
Off-center abundance enhancement is sign of a merger. Temperature map indicates the Geometry.



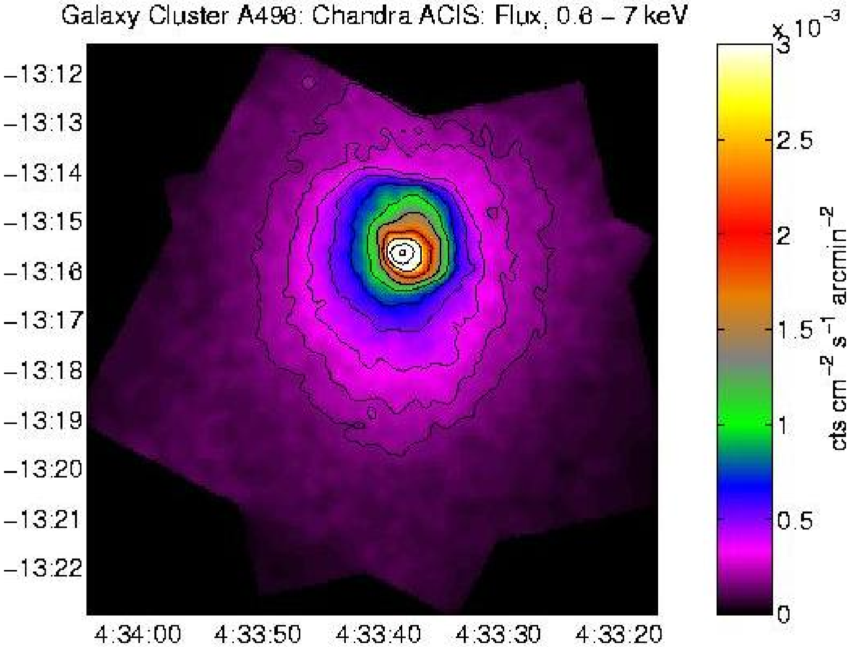


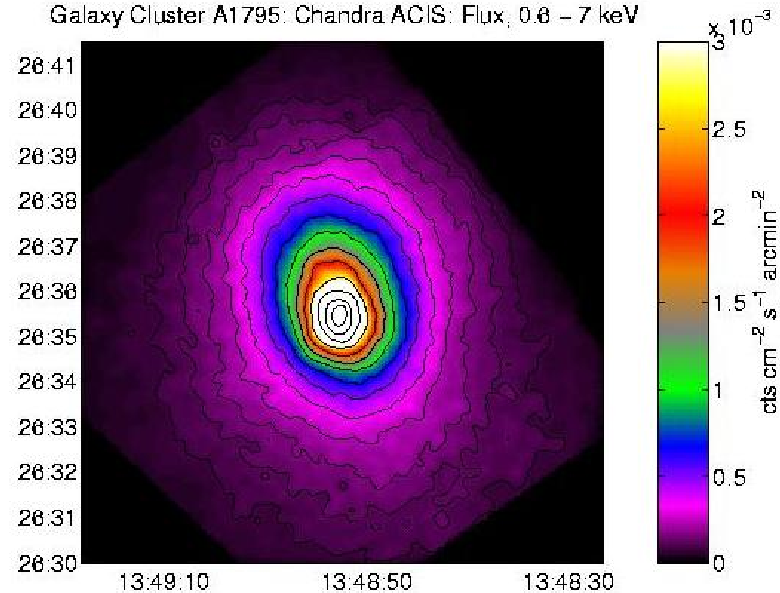
Above left: Chandra hardness map of the central region of Abell 3266. There Is a double nucleus cD ("dumbbell") with very high relative velocity.
Above right: XMM entropy map of the central region. In both cases, low Temperature, low entropy gas "blobs" mark the trail of the merger.

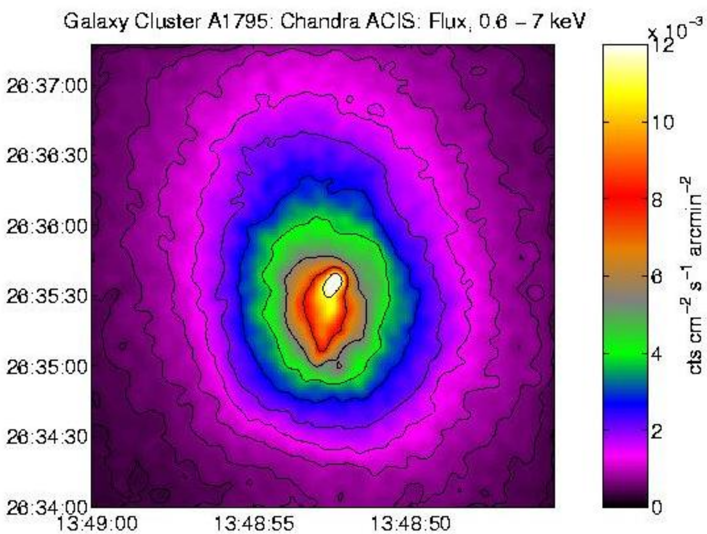




<u>Above left:</u> Iron map from Chandra ACIS. Above right <u>Sulphur map</u>. High S/Fe ratio in the central region may indicate dominance of Type II Supernovae (SNII) in this region. SNII have massive stars as progenitors and are therefore rich in α-elements (Si, Mg, S…) relative to Fe. High S/Fe ratio may be indicative of recent Episode of star formation.


Galaxy Cluster A496: Chandra ACIS: Flux, 0.6 – 7 keV
−13:12
−13:13
−13:14
−13:15
−13:16
−13:17
−13:18
−13:19
−13:20
−13:21
−13:22
4:34:00
4:33:50
4:33:40
4:33:30
4:33:20
x 10^−3
3
2.5
2
1.5
1
0.5
0
cts cm^−2 s^−1 arcmin^−2


Galaxy Cluster A1795: Chandra ACIS: Flux, 0.6 – 7 keV
26:41
26:40
26:39
26:38
26:37
26:36
26:35
26:34
26:33
26:32
26:31
26:30
13:49:10
13:48:50
13:48:30
x 10^−3
3
2.5
2
1.5
1
0.5
0
cts cm^−2 s^−1 arcmin^−2


Galaxy Cluster A1795: Chandra ACIS: Flux, 0.6 – 7 keV
26:37:00
26:36:30
26:36:00
26:35:30
26:35:00
26:34:30
26:34:00
13:49:00
13:48:55
13:48:50
x 10^−3
12
10
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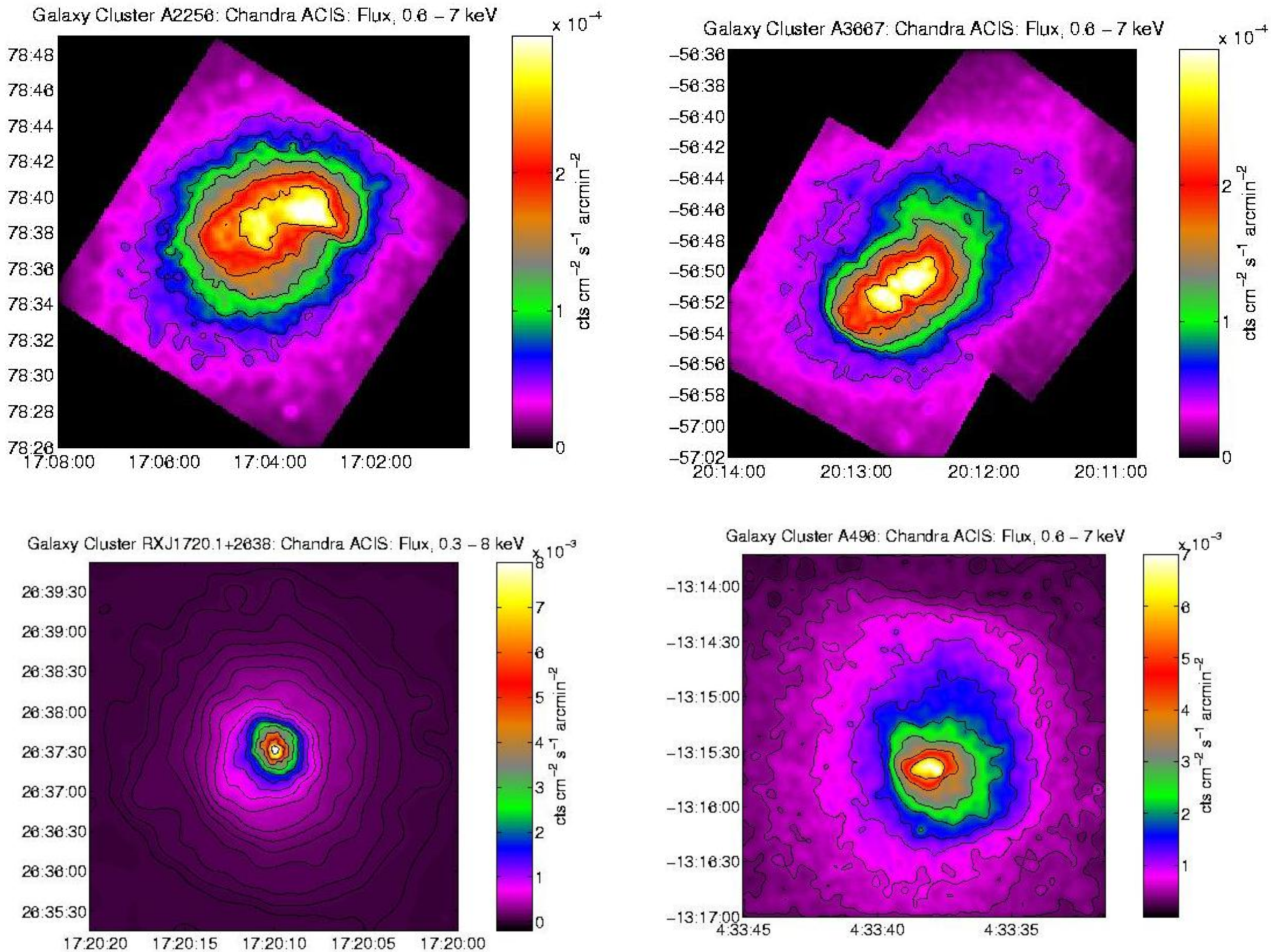
cts cm^−2 s^−1 arcmin^−2


Galaxy Cluster A2256: Chandra ACIS: Flux, 0.6 – 7 keV
78:48
78:46
78:44
78:42
78:40
78:38
78:36
78:34
78:32
78:30
78:28
78:26
17:08:00
17:06:00
17:04:00
17:02:00
x 10^-4
2
1
0
cts cm^-2 s^-1 arcmin^-2
Galaxy Cluster A3667: Chandra ACIS: Flux, 0.6 – 7 keV
−56:36
−56:38
−56:40
−56:42
−56:44
−56:46
−56:48
−56:50
−56:52
−56:54
−56:56
−56:58
−57:00
−57:02
20:14:00
20:13:00
20:12:00
20:11:00
x 10^-4
2
1
0
cts cm^-2 s^-1 arcmin^-2
Galaxy Cluster RXJ1720.1+2638: Chandra ACIS: Flux, 0.3 – 8 keV
26:39:30
26:39:00
26:38:30
26:38:00
26:37:30
26:37:00
26:36:30
26:36:00
26:35:30
17:20:20
17:20:15
17:20:10
17:20:05
17:20:00
x 10^-3
8
7
6
5
4
3
2
1
0
cts cm^-2 s^-1 arcmin^-2
Galaxy Cluster A496: Chandra ACIS: Flux, 0.6 – 7 keV
−13:14:00
−13:14:30
−13:15:00
−13:15:30
−13:16:00
−13:16:30
−13:17:00
4:33:45
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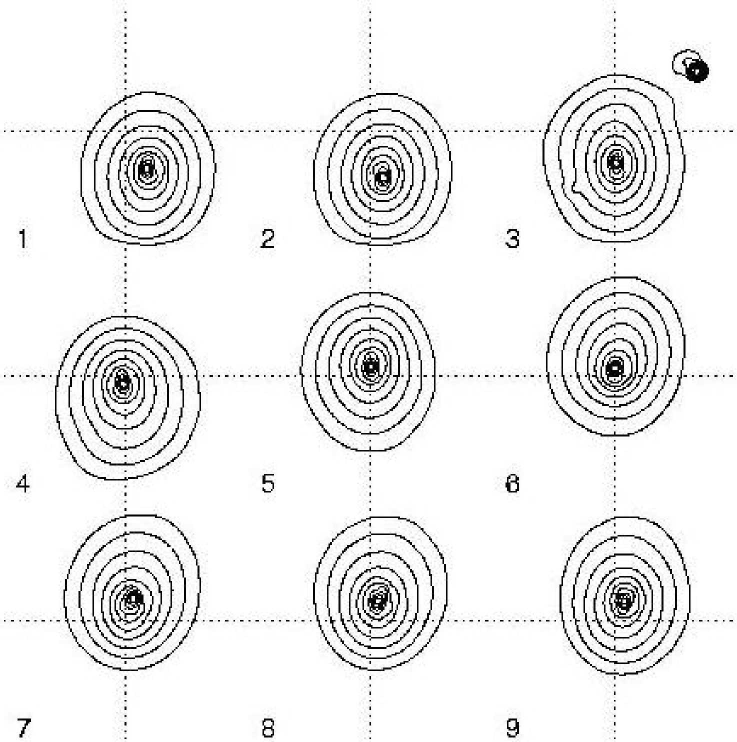
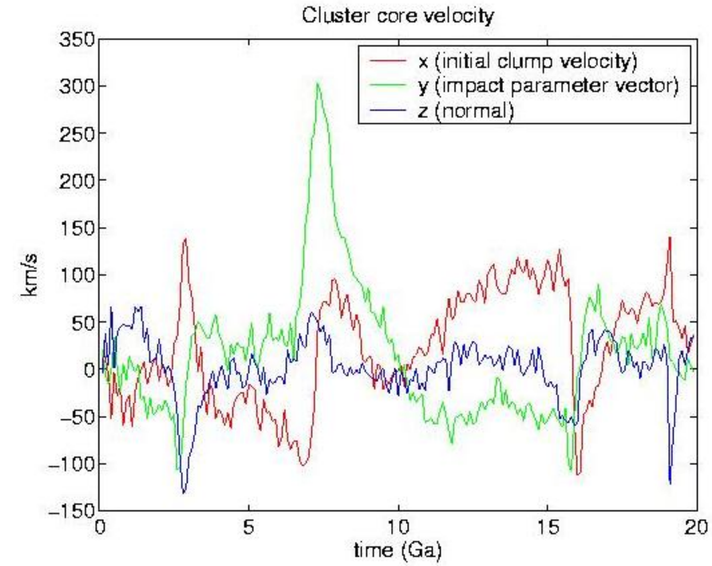
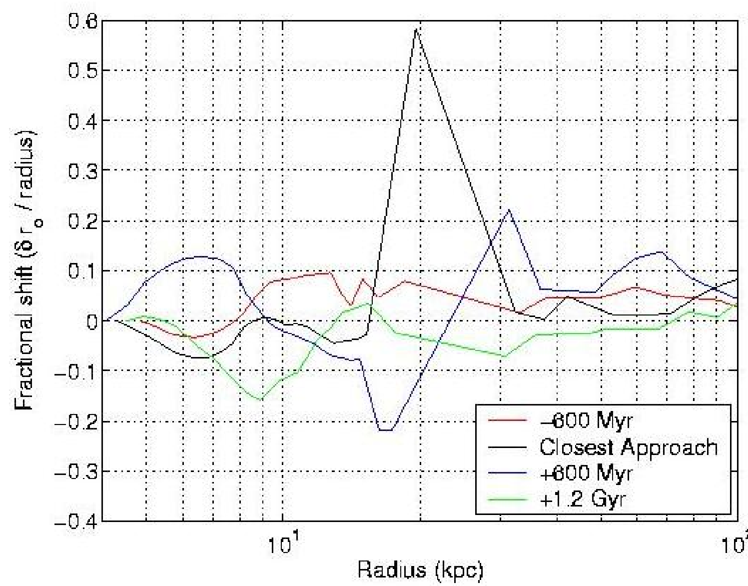
cts cm^-2 s^-1 arcmin^-2







Simulations of primary core sloshing
Induced by a interaction with a subcluster.
<u>Above left:</u> predicted morphologies. <u>Above Right:</u> sloshing amplitude. <u>Below right:</u> shift of Core vs. time. Chandra “Cold front” morphology May be evidence of past interaction.